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Flow Properties of a Free Molecule Micro-Resistojet for Small Spacecraft Applications *

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1 Introduction

Interest in low cost space operations and exploration has encouraged the investigation of small satellite constellations which enhance the performance of tasks previously performed by a few much larger spacecraft. Satellite constellations consisting of several spacecraft with masses between 0.01 and 100 kg will be used for various missions [1]. The growing trend towards the use of large numbers of small spacecraft operating in local clusters or constellations has created a critical requirement for low power, efficient propulsion systems.

There is a growing realization that, in many cases, microthrusters will not be simply scaled down versions of present thruster systems. For example, to maintain efficiency at small scales for chemical thrusters requires a significant increase in operating pressure to maintain equivalent levels of frozen flow and viscous losses which may be incompatible for MEMS valves. Typical nozzle expansions require throat diameters on the order of tens of microns which are easily plugged by particulates [2]. Therefore, there is a viable requirement for novel microthrusters which, from a systematic point of view, offer several benefits over conventional, scaled down versions of existing thrusters.

A free molecule micro-resistojet (FMMR) thruster concept has been developed which offers several distinct advantages over conventional microthruster concepts for attitude control and station keeping maneuvers. The FMMR combines microelectromechanical systems (MEMS) fabrication techniques with simple, lightweight construction as shown schematically in cross section in Fig.1. The FMMR consists of a polysilicon thin film heating element at a temperature T_w and a long expansion slot. A slot is chosen as an advantage over a small nozzle expansion because of the possibility of catastrophically plugging a small orifice (typically on the order of 10 μm in diameter) by contaminants.

In the case of the FMMR, the characteristic dimension defining free molecule flow is taken as the slot width, w. The design requirement is to arrange that the last surface contact by a molecule before it exits through the slot is with the heated surface. Although the free molecule condition sacrifices thruster performance over an ideal continuum expansion, the added benefits of simple construction, reduced risk of nozzle plugging, reduced propellant storage pressure, and simplified valve requirements make the FMMR attractive for several mission requirements.

The figure of merit for thruster performance is the specific impulse (I_{sp}) or generated thrust per unit propellant mass flow [3]. In free molecule flow, the specific impulse varies as $(T_o/m)^{1/2}$ where T_o is the propellant gas stagnation temperature and m is the propellant molecular mass. The ratio of the specific impulse for limit expansion through an ideal nozzle to that for free molecule flow through a slot depends on the propellant but is approximately two.

In the present problem, we use parametric, direct simulation Monte Carlo (dsMC) [4] numerical simulations to measure the enhancement of thrust made possible by local / differential surface heating of the rarefied propellant gas in a relatively easily-fabricated and robust MEMS structure. The simple one-dimensional, stationary gas, free-molecular results used in this study are expected to be useful in basic design, however, the actual micro-resistojet involves multidimensional transitional rarefied gas flow, and more sophisticated analysis methods are required for accurate performance predictions.

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2 Results

Fig.2 shows typical flowfield results for the nominal case (T_w = 600K, T_o = 300K) oriented in the horizontal direction. The contours consist of raw data, with each pixel corresponding to a flowfield cell, and give an indication of grid resolution. The upper half of the figure shows translational temperature contours. At this rarefaction, slip phenomena are expected to be large. This feature is confirmed by the peak temperature in the gas near the pedestal remaining much lower than the pedestal wall surface temperature. The lower half of the figure shows axial velocity contours. The acceleration of the gas due to the slot expansion is evident, while near the slot wall large velocity slip occurs. These results assume that all thruster walls are fully accommodating.

A parametric study has shown the effect of the slot divergence angle on performance or specific impulse. Comparison of the axial components of slot surface pressure and shear forces indicate that the slot expansion provides net positive increment to performance for the smaller angles (40 to 60 degrees) and lengths (250 μm) considered. The relatively large shear losses indicate that for these highly rarefied flows, small expansion ratios (or short slot heights) are preferable. The limiting case of 90 degrees results in a constant width slot, where only shear losses arise, leading to poor performance. A maximum in the specific impulse is achieved near 60 degrees for a Knudsen number of approximately one, indicating a maximum in the difference between the slot surface pressure and the shear force along the slot expansion wall.

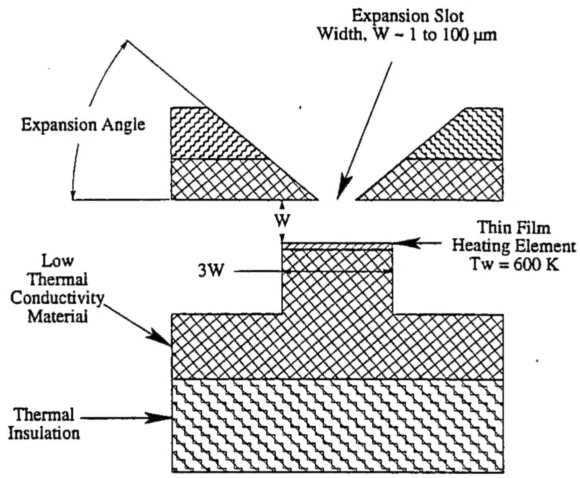

Figure 1: Free Molecule Micro-Resistojet (FMMR) conceptual design schematic

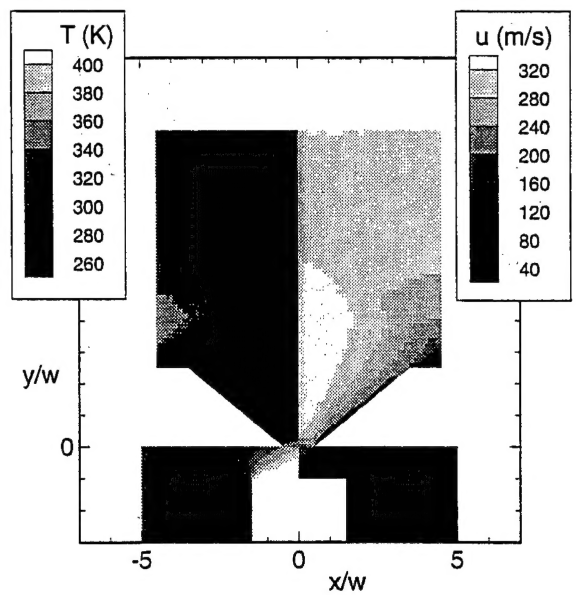

Figure 2: Translational temperature and axial velocity contours for T_w = 600 K and T_o = 300 K

3 Conclusions

The scope of this research addresses the FMMR flowfield properties as a function of several parameters including the gas/surface interaction model, FMMR geometry, propellant stagnation temperature and pressure, and slot divergence angle. Of particular interest will be the effect of the slot expansion on thruster performance. A complete parametric evaluation of thruster performance will be presented in the final manuscript.

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